

Exploring the infrared/radio correlation at high redshift

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Accepted 2008 February 5; Received 2008 January 11; in original form 2007 October 9

ABSTRACT

We have analysed the 24- μ m properties of a radio-selected sample in the Subaru-*XMM/Newton* Deep Field in order to explore the behaviour of the FIR/radio relation at high redshifts. Statistically, the correlation is described by q_{24} , the ratio between the observed flux densities at 24 μ m and 1.4 GHz, respectively. Using 24- μ m data results in considerably more scatter in the correlation than previous work using data at 60–70 μ m. Nevertheless, we do observe a steady correlation as a function of redshift, up to $z \approx 3.5$, suggesting its validity back to primeval times. We find $q_{24} = 0.30 \pm 0.56$ for the observed and $q_{24} = 0.71 \pm 0.47$ for the k -corrected radio sample, based on sources with $300 \mu\text{Jy} < S_{1.4\text{GHz}} < 3.2 \text{ mJy}$ and 24 μ m detections. A suitable k -correction given by a M82-like mid-IR template suggests no extreme silicate absorption in the bulk of our radio sample. Using thresholds in q_{24} to identify radio-excess sources, we have been able to characterise the transition from radio-loud AGN to star-forming galaxies and radio-quiet AGN at faint ($\lesssim 1 \text{ mJy}$) radio flux densities. Our results are in broad agreement with previous studies which show a dominant radio-loud AGN population at $> 1 \text{ mJy}$. The rest-frame $U - B$ colours of the expected radio-excess population have redder distribution than those that follow the correlation. This is therefore a promising way to select obscured Type-2 AGN, with a radio loud nature, missed by deep X-ray observations. Spectroscopic follow-up of these sources is required to fully test this method.

Key words: starburst – galaxies: active – galaxies: high-redshift – galaxies: classification, colours – galaxies.

1 INTRODUCTION

The far-infrared/radio (FIR/radio) relation is one of the tightest correlations known in astronomy. Established over three decades ago (e.g. Van der Kruit 1971; Helou et al. 1985), it covers about five orders of magnitude in luminosity (Condon 1992; Garrett 2002). The correlation is tightest for local star-forming galaxies and relates the integrated thermal emission, from the dust present in star-forming regions, with the non-thermal synchrotron emission produced by relativistic particles (cosmic rays) accelerated by supernovae explosions (Harwit & Pacini 1975). A complete explanation of the origin of this remarkable correlation is essential for our understanding of how galaxies formed and evolved, particularly if the correlation ex-

tends from primeval galaxies to the fully mature galaxies observed locally, as recent studies have hinted (Kovács et al. 2006).

Being relatively direct probes of recent star formation, FIR and radio data are amongst the most powerful tools available to test whether primordial galaxies shared the same properties as galaxies present today. Low-frequency radio data has been used to estimate redshifts using radio-to-submm flux density ratios (e.g. Carilli & Yun 2000), and to determine the cosmic star formation history (e.g. Haarsma 2000; Ivison et al. 2007a), facilitating the investigation of the cosmic IR background (CIRB). If the relation between flux densities observed in the FIR and radio wavebands holds at high redshifts, then we can exploit ultra-deep high-resolution radio imaging to resolve the CIRB and to explore the properties of luminous distant galaxies – for example, studies of submm (or “SCUBA”) galaxies (Smail et al. 1997; Hughes et al. 1998) which are encum-

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bered by the confusion encountered in the submm (rest-frame FIR) waveband, and studies of active galactic nuclei (AGN; Beelen et al. 2006) that are subject to selection biases caused by obscuration at shorter wavelengths.

While the combination of *Spitzer* observations at 24 and 70 μm and radio observations at 1.4 GHz support the universality of the FIR/radio correlation up to a redshift of approximately unity (Appleton et al. 2004), extending this correlation to higher redshifts requires extremely deep and complementary observations at radio and IR wavelengths, as well as reliable estimates of redshift. The work presented here is based on a deep multi-wavelength study in the Subaru-*XMM/Newton* Deep Field (SXDF). We have exploited 1.4-GHz images from the Very Large Array (VLA), reaching a 5σ flux density threshold of $\sim 35 \mu\text{Jy}$ and covering an area of approximately 1 deg^2 . The region has also been observed to impressive depths at optical (SuprimeCAM; Furusawa et al. in preparation), near-IR (UKIDSS-UDS; Lawrence et al. 2007) and mid-IR (*Spitzer* Wide-area IR Extragalactic Survey – SWIRE; Lonsdale et al. 2003) wavelengths.

Starburst galaxies, radio-quiet and radio-loud AGN are the three main populations which can be observed to high redshifts with the data employed in this work. It is known that radio-quiet AGN (i.e. Seyfert galaxies) follow the FIR/radio correlation (Roy et al. 1998), but radio-loud AGN may vary considerably in radio luminosities due to their extra core and jet radio emission, thus weakening and biasing the correlation. In theory, it is possible to identify these radio-loud AGN via their deviation from the expected relation and therefore to determine the fraction of these so-called “radio-excess” sources as a function of radio flux density. This would then allow us to constrain the predictions of synthesis population models for the transition at sub-mJy radio fluxes from radio-loud AGN to starburst/radio-quiet AGN (Dunlop & Peacock 1990; Jarvis & Rawlings 2004).

The aim of this work is to explore and discuss the correlation between the monochromatic fluxes at 24 μm and 1.4 GHz across a broad range of redshifts and test the capabilities of the relation for selecting radio-loud AGN (e.g., Donley et al. 2004).

In Section 2, we present the multi-wavelength data available for the SXDF field and used in this work. Section 3 shows the capabilities of the data to extend the 24 μm /1.4 GHz correlation to higher redshifts and Section 4 describes the process of detecting radio-loud AGN at sub-mJy 1.4-GHz flux densities. The discussion and conclusions are presented in Section 5 and 6 respectively. Throughout this paper we have used $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Spergel et al. 2007).

2 SXDF OBSERVATIONS

2.1 Radio observations at 1.4 GHz

Radio observations of the SXDF were carried out by Ivison et al. (2007b) during July 2003 using the VLA at 1.4 GHz. The total integration time was approximately 60 hours, reaching an r.m.s. depth of $7 \mu\text{Jy beam}^{-1}$ near the centre of the field. The radio map is centred at R.A. 2h 18m, Dec. $-5^\circ 0'$, with a synthesised beam of $1.86 \text{ arcsec} \times 1.61 \text{ arcsec}$ at position angle 15° . The source detection was carried out using a 5σ threshold, sufficient to avoid significant contamination by spurious sources, obtaining a total number of 563 radio sources in an area of $\sim 0.45 \text{ deg}^2$.

In order to exploit the larger area covered by previous multi-wavelength observations in the SXDF, we have also used the 1.4-

GHz catalogue presented by Simpson et al. (2006). Their observations comprised thirteen VLA pointings reaching a mosaic r.m.s. noise of $\sim 12\text{--}20 \mu\text{Jy beam}^{-1}$. The Simpson et al. catalogue contains 505 sources and covers 0.8 deg^2 to a flux density limit of $100 \mu\text{Jy}$.

By combining both radio samples, we obtained a total sample of 828 radio sources. Extended sources and obvious doubles, identified by eye, were considered as single emitters. The distribution of radio flux densities peaks at about $100 \mu\text{Jy}$ and reaches flux densities as faint as $35 \mu\text{Jy}$ (5σ) and as bright as 80 mJy .

2.2 *Spitzer* observations

The SXDF was observed by *Spitzer* as part of the *Spitzer* Wide-area Infrared Extragalactic Survey (SWIRE; Lonsdale et al. 2003) Legacy programme. The SXDF is included in one of the seven high-latitude SWIRE fields, the *XMM*-LSS field, with coverage of 9.1 deg^2 . Observations were obtained at 3.6, 4.5, 5.8 and 8.0 μm with IRAC and at 24, 70 and 160 μm with MIPS (Surace et al. 2005). In order to explore the FIR/radio correlation, we have used only the detections at 24 μm . It is known that use of the monochromatic 24- μm flux densities yields a larger scatter than the 70- μm data (Appleton et al. 2004); however, we are limited by the relatively shallow coverage at 70 μm and the more severe confusion at that wavelength.

To explore the FIR/radio relation as a function of redshift, we use the combined radio source catalogue described in §2.1 to cross-match it with the conservative (10σ) SWIRE source catalogue retrieved from the *Spitzer* Centre Archive. We obtained 370 counterparts with fluxes $S_{24\mu\text{m}} \gtrsim 0.4 \text{ mJy}$ using a 12.5-arcsec-diameter aperture for the photometry.

We then extended the catalogue to fainter 24- μm flux densities by measuring the observed flux density on the 24- μm map, using the same diameter aperture centred at the radio positions. This allowed the inclusion of 125 sources with 24- μm flux densities of $S_{24\mu\text{m}} \gtrsim 200 \mu\text{Jy}$ ($\sim 4\sigma$; Shupe et al., 2007). In this paper, for all the remaining radio sources we used upper limits at $S_{24\mu\text{m}} = 200 \mu\text{Jy}$.

2.3 Subaru and UKIRT Observations

The SXDF is home to the very deep optical survey undertaken by Subaru/SuprimeCAM (Miyazaki et al. 2002). This comprises five overlapping pointings, providing broad-band photometry in the *BVRi'z'* filters to typical 5σ (AB magnitude) depths of $B = 27.5$, $V = 26.7$, $R = 27.0$, $i' = 26.8$ and $z' = 25.9$, respectively (2-arcsec-diameter apertures). The seeing in the composite images is $\sim 0.8 \text{ arcsec}$ (Sekiguchi et al. 2005, Furusawa et al. 2008).

The central region of the SXDF is also being observed at near-IR wavelengths with the Wide-Field Camera (WFCAM) on the 3.8-m United Kingdom Infrared Telescope (UKIRT). As the deepest tier of the UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007), the Ultra Deep Survey (UDS) aims to cover 0.8 deg^2 to $K_{\text{AB}} = 25$. In this work, we use the UKIDSS First Data Release (DR1; Warren et al. 2007) where the 5σ point source depths (in AB magnitudes) at *J* and *K* are 23.61 and 23.55, with seeing of 0.86 and 0.76 arcsec, respectively.

We have used the *K*-band as the reference to cross-match with all other near-IR and optical images. Unfortunately, the UDS map misses part of the radio coverage of the SXDF field, limiting the radio sample to an area with 726 radio sources, out of which 639 (88 per cent) have clear counterparts in the UDS *K* data within a search radius of 1.5 arcsec.

2.4 Photometric redshifts

We obtained reliable photometric redshifts for 586 of the radio sources detected at near-IR wavebands. The estimation was carried out using all available detections from the B, V, R, i', z', J, K , 3.6- μm and 4.5- μm photometric bands and considering a conservative criteria: not including either those sources with poor χ^2 fitting nor those contaminated by halos from nearby stars.

The spectral energy distribution (SED) fitting procedure provides a photometric estimation consistent within $\Delta z/(1+z) = 0.05 \pm 0.04$ for the UDS galaxies in general (see Cirasuolo et al. 2007 for details), and spectroscopic redshifts available for 63 of the 586 radio sources (Yamada et al. 2005, Simpson et al. 2006 and the NASA Extragalactic Database) indicate that the photometric redshifts of the radio sources are also accurate at this level. The precision of this estimation is good enough to allow an adequate k -correction to the data (see Figure 1). The resulting redshift distribution of the radio sources peaks at about $z \sim 0.7$ and includes galaxies up to $z \approx 3.5$.

Note that since the photometric redshift estimation depends on the K-band detection, the sample is basically mass limited. Dwarf galaxies with faint radio emission may be missed in the K-band, but massive ones are expected to be detected up to very high redshift. Heavily obscured galaxies, however, are not drastically affected.

3 THE FIR/RADIO RELATION

Based on the analysis presented in Section 2, 369 sources (out of potentially 726 due to the missed UDS area) have both a 24- μm detection with flux density $S_{24\mu\text{m}} > 200 \mu\text{Jy}$ and a reliable redshift (49 of which are spectroscopic).

We present in Figure 1 the FIR/radio relation in terms of the basic observable parameter, q_{24} – the ratio between the monochromatic fluxes at 24 μm and 1.4 GHz, $\log(S_{24\mu\text{m}}/S_{1.4\text{GHz}})$ – as a function of redshift. Ideally, the correlation should be calculated using the bolometric FIR flux, however the paucity of long-wavelength data makes this quantity difficult to estimate prior to the future arrival of SCUBA-2 (Holland et al. 2006) and/or the *Herschel Space Observatory* (Poglitsch et al. 2006).

3.1 Non k -corrected data

Figure 1 shows that the vast majority of the sources detected at 24 μm follow a tight correlation between q_{24} and redshift, up to $z \approx 3.5$. Upper limits have been included using $S_{24\mu\text{m}} = 200 \mu\text{Jy}$ and show probable evidence for a large number of radio-excess sources (i.e. radio-loud AGN) at the observed radio flux density regime.

K -corrections to the data have been tested assuming standard starburst galaxy templates for the 24 μm detections and a simple power slope for the radio density fluxes. The expected variations of q_{24} as a function of redshift are overplotted in Figure 1 and are used to study and characterise the distribution for star-forming galaxies. Nevertheless, the presence of radio-loud AGN sources in the sample introduces outliers in the correlation that may cover a wide range of q_{24} values due to radio excess emission coming from core and jet structures. For example, the radio-loud AGN such as Cygnus A (a powerful double-lobed radio galaxy) and Centaurus A (one of the closest known radio galaxies) have $q_{24} = -3.2$ and -1.1 values, respectively, far away from the main data trend from Figure 1. In particular, our data show that the population with

$S_{1.4\text{GHz}} > 3.2 \text{ mJy}$ ($10^{-2.5} \text{ Jy}$; large squares in Figure 1), characterised to be AGN-dominated by Condon (1992), have $q_{24} \lesssim -1$, well below the bulk of the data points and similar to the estimation obtained from a composite radio-loud AGN template (Elvis et al. 1994). Since we expect and want a correlation valid for star-forming systems, sources with $S_{1.4\text{GHz}} > 3.2 \text{ mJy}$ are excluded from our analysis of the FIR/radio correlation, basically because these sources are radio-loud AGN that introduce biases in the statistics.

Using the biweight estimator¹ (Beers et al. 1990) to characterise the data, we find a central location (mean) and scale parameter (sigma; all q_{24} values quoted in this paper will similarly be given in this way) given by $q_{24} = 0.66 \pm 0.39$ (based on all detections at 24 μm including sources without estimated redshifts). The sub-sample of sources with $0 < z < 1$ gives an observed $q_{24} = 0.80 \pm 0.33$, in agreement with the results of Appleton et al. (2004), i.e. $q_{24} = 0.84 \pm 0.28$. The data also suggest a decreasing trend of q_{24} as a function of redshift. A simple linear regression to the 24 μm -detected sources with estimated redshift gives a dependency $q_{24}(z) = (0.85 \pm 0.01) + (-0.20 \pm 0.01)z$. Nevertheless, this trend is probably seen because data have not been k -corrected (Hogg et al. 2002) as we describe later. It is worth noticing that the available 49 sources with spectroscopic redshifts support the validity of the photometric estimation at high redshift (large circles in Figure 1).

3.2 k -corrected data

IR spectroscopic studies of local starburst galaxies have shown three main components in the mid-IR range (5–38 μm): silicate bands around 10 and 18 μm , a large number of PAH emission features, and a slope of the spectral continuum, where an AGN may be present (Brandl et al. 2006). In order to model the k -correction to the mid-IR emission from the bulk of the star-forming sources, we have convolved the SED of M82 (a local standard starburst galaxy with a distribution obtained from a fit to the observed photometry presented by Silva et al. 1998), Arp 220 (obtained from photometry listed in the NASA/IPAC Extragalactic Database and compiled by Pope et al. 2006) and a model of an ultraluminous IR galaxy (ULIRG; $L_{\text{IR}} = 10^{12} L_{\odot}$) given by Lagache et al. (2004), with the 24- μm filter profile from *Spitzer*/MIPS. The radio emission is assumed to be well represented by a power law with a spectral index $\alpha = -0.7$, based on an average steep-spectrum radio source (Condon 1992).

Note that assumptions of different mid-IR templates may largely change the q_{24} values at high redshift, mainly due to the 10- μm silicate feature redshifted to $z \approx 1.5$, where variations of even an order of magnitude in k -correction are seen. On the other hand, if we consider an extreme error in the radio spectral slope of $\sigma(\alpha) = 0.5$ (see findings in Garn et al. 2007), we find that the k -correction may change in ~ 0.3 dex at $z \approx 3.5$, a value much lower than the 24 μm uncertainties.

The overplotted lines, in Figure 1, show the expected change in the observed q_{24} parameter as a function of redshift based on the different adopted templates. Apart from the composite radio-loud spectra, the k -corrections have been normalised to the best fit to the data.

¹ In order to statistically describe the data, we used the biweight estimator which is resistant to outliers and is also robust for a broad range of non-Gaussian distributions. This is essential to remove remaining AGN from the statistics of the sample.

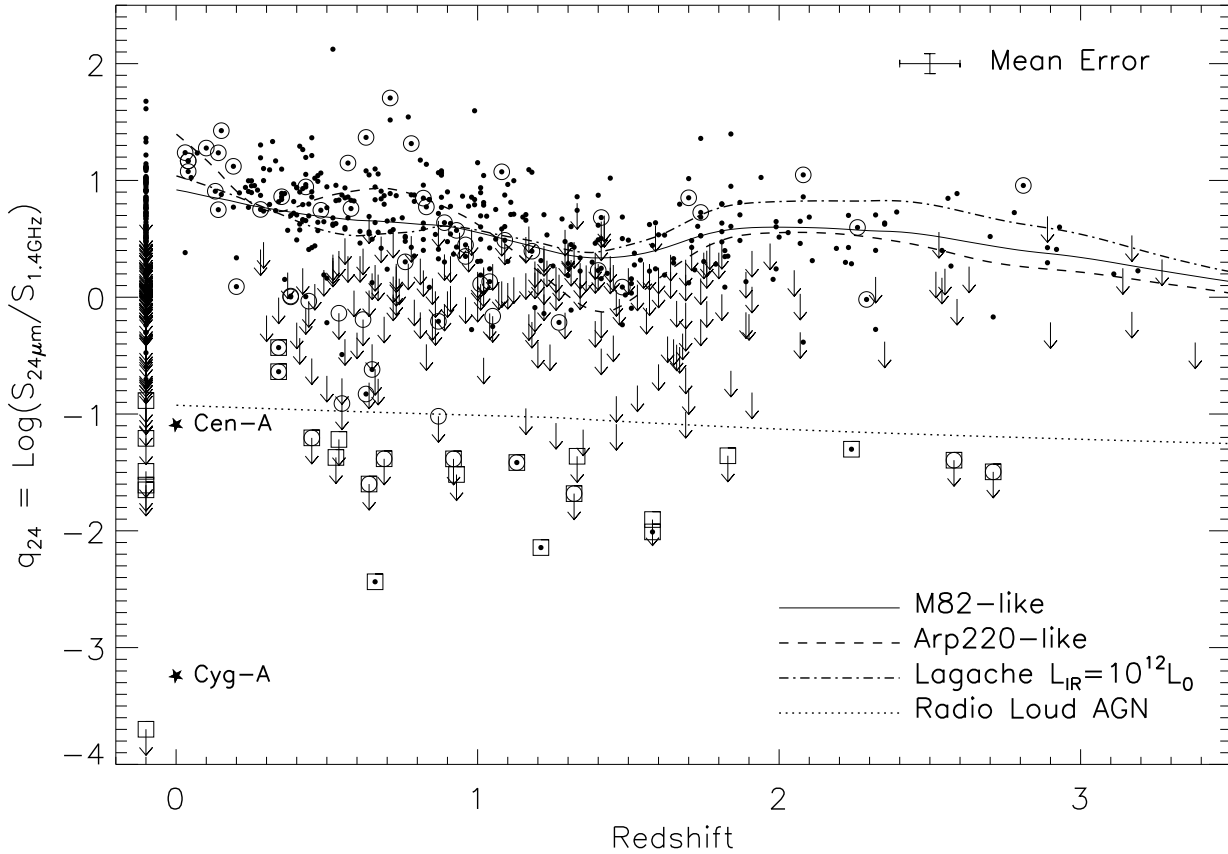


Figure 1. *Black dots:* ratio between the observed monochromatic fluxes at 1.4 GHz and 24 μm , $q_{24} = \log(S_{24\mu\text{m}}/S_{1.4\text{GHz}})$, as a function of redshift. *Downward arrows:* upper limits considering a mid-IR flux threshold given by 200 μJy . Note that these data have not been k -corrected. Sources without photo- z 's are plotted at $z = -0.1$. *Large circles:* sources with spectroscopic redshifts. *Large squares:* sources with radio flux densities $S_{1.4\text{GHz}} > 3.2 \text{ mJy}$. Uncertainties in the observed flux densities give an average q_{24} mean error of ~ 0.1 dex, and error bars in redshift are approximately $\sigma_z \approx 0.1$ (Cirasuolo et al. 2007). Overplotted lines show different k -correction factors, $K(24\mu\text{m})/K(1.4\text{GHz})$, for the observed q_{24} values as a function of redshift. The assumed mid-IR templates were convolved with the 24- μm filter from *Spitzer*/MIPS and are used to show the expected variation of the q_{24} values as a function of redshift. Three of these mid-IR templates are based on star-forming galaxies: two local standard massive starburst galaxies, M82 and Arp 220, and a SED model for an ULIRG galaxy with $L_{\text{IR}} = 10^{12} L_{\odot}$, as described by Lagache et al. (2004). All these three templates are assumed to have a simple spectral index $\alpha = -0.7$ for the radio emission, where $S_{\nu} \propto \nu^{\alpha}$, and normalised to the best fit to the data detections. Finally, a composite spectrum for radio-loud AGN given by Elvis et al. (1994) is also included, although as indicated by the locations of Cen-A and Cygnus-A, radio-loud AGN may be distributed over a wide range of q_{24} values. In particular, this template is not normalised to the best fit but uses values from the actual composite spectrum at both wavelengths.

A descending trend in q_{24} as a function of redshift is expected from all three starburst-like k -corrections, in agreement with the observed slope. The k -corrected relation based on sources with mid-IR detections ($> 200 \mu\text{Jy}$) and estimated redshifts, changes to $q_{24} = 0.99 \pm 0.32$, 1.45 ± 0.38 , and 1.08 ± 0.37 (biweight estimator) using the M82-like, Arp 220-like and the Lagache et al. model, respectively. The M82-like k -corrected q_{24} values are presented in the upper panel of Figure 2 to demonstrate the improvement in the correlation as a function of redshift. Figure 3 shows a redshift-binned version of this plot (for the 24 μm detected sources), demonstrating that both the mean and scatter of the M82-like k -corrected q_{24} value remain constant out to $z \sim 3.5$; it also demonstrates that k -correcting with an Arp220-like spectrum leads to large variations in the relation with redshift. Based upon the behaviour of the M82-like k -corrected distribution, and particularly the lack of a clear excess in scatter for sources between $1 < z < 2$, we suggest no strong MIR-silicate absorption for the bulk of the sources.

The M82-like k -correction to all sources with detections at 24 μm in the range $0 < z < 1$ gives $q_{24} = 1.03 \pm 0.31$, in agreement with previous Appleton et al. (2004) estimation ($q_{24} = 1.00 \pm 0.27$). A simple linear regression to the M82-like k -corrected data is given by $q_{24}(z) = (0.94 \pm 0.01) + (-0.01 \pm 0.01)z$, suggesting a constant dependency (at 1σ level) for the q_{24} fraction with redshift. This result assumes that all galaxies in the sample can be fitted with a single M82-like template, although the fact that the correlation naturally appears to have the same mean and scatter as a function of redshift, up to $z \sim 3.5$, is highly suggestive that the FIR/radio correlation holds all the way back to primordial times.

3.3 The correlation based on a complete radio sample at 24 μm

The mean and scatter values quoted for the correlations described above may be being biased by incompleteness at 24 μm for sources

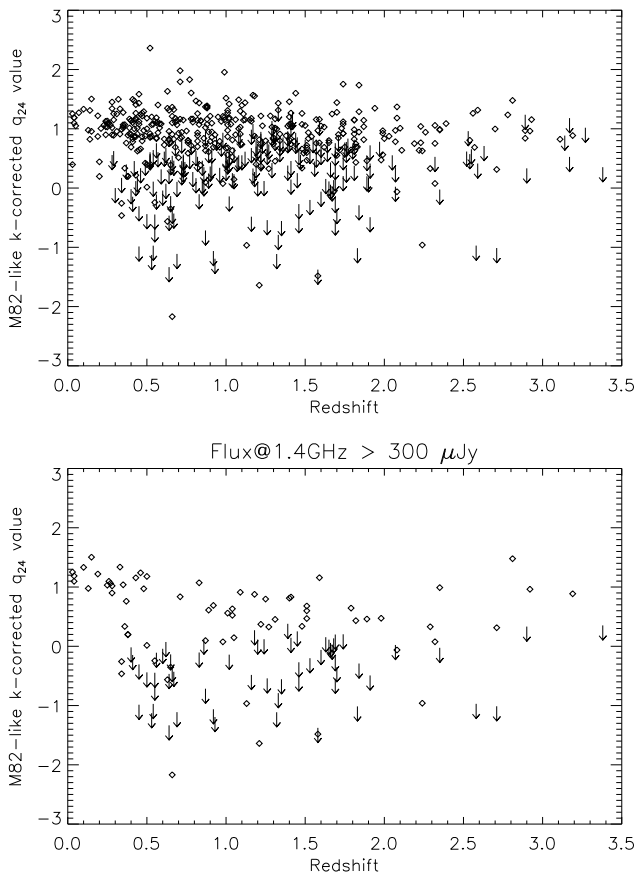


Figure 2. K -corrected q_{24} values as a function of redshift. The k -correction uses a M82-like template (Silva et al. 1998) for the mid-IR and a spectral slope $\alpha = -0.7$ for the radio emission ($S_\nu \propto \nu^\alpha$). *Top*: Full radio sample. *Bottom*: Radio sources with 1.4-GHz flux densities above $300 \mu\text{Jy}$. Upper limits are considered at $S_{24\mu\text{m}} = 200 \mu\text{Jy}$.

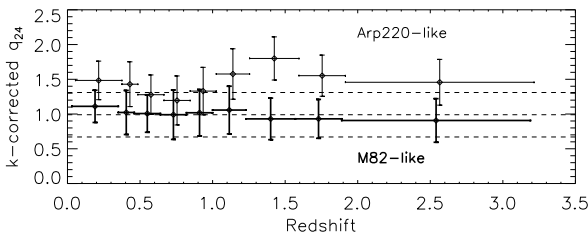


Figure 3. Binned mean and scatter of the M82-like k -corrected $24\mu\text{m}/1.4\text{GHz}$ correlation (thick black data) as a function of redshift, based on the full radio sample. The overplotted lines correspond to the mean and one sigma limits, for the all-redshift distribution. Also shown (in thin black data) are the equivalent values for an Arp220-like k -correction (shifted in redshift by a small factor in order to improve the visualisation only), which results in considerably more residual redshift variation. Note that the significantly higher q_{24} values for the Arp220-like k -correction results from the upturn in the Arp220-like correction at $z < 0.3$ and due to the particularly extreme silicate absorption features (cf. Figure 1).

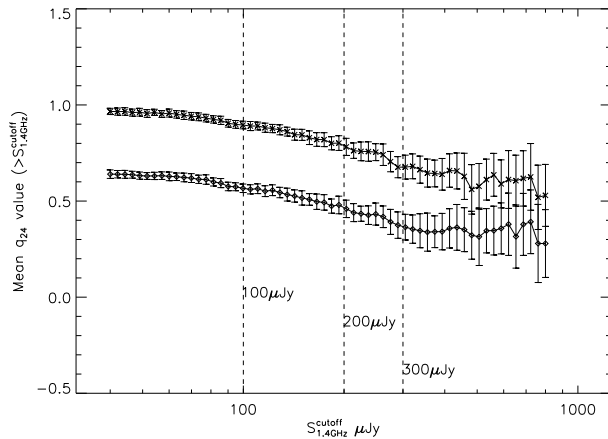


Figure 4. Mean q_{24} value as a function of cut-off in radio flux density. Diamonds and crosses are based on the observed and M82-like k -corrected data, respectively, both showing similar dependencies with the cut-off in radio. The error bars represent the uncertainty on the mean value estimated using boot-strap re-sample technique. The vertical dashed lines are at $100 \mu\text{Jy}$, $200 \mu\text{Jy}$ and $300 \mu\text{Jy}$. Since sources with $S_{1.4\text{GHz}} > 3.2\text{mJy}$ ($10^{-2.5}\text{Jy}$) are essentially all radio-loud AGN (Condon 1984), these were not included in the estimation for the mean value.

with faint radio fluxes: a large number of star-forming dominated radio sources with $S_{1.4\text{GHz}} \lesssim 300 \mu\text{Jy}$ are not expected to have been detected at $24 \mu\text{m}$. To demonstrate this problem, we plot in Figure 4 the mean q_{24} as a function of a cut-off in the 1.4-GHz flux density. It clearly shows a decreasing trend for the mean q_{24} from fainter radio fluxes up to $S_{1.4\text{GHz}} \approx 300 \mu\text{Jy}$, where a flattening starts to appear. This means that considering a high enough radio cut-off, the correlation becomes independent of the radio sample. We, therefore, base the correlation on a complete radio sample by constraining the number of sources to those with $S_{1.4\text{GHz}} > 300 \mu\text{Jy}$. This radio sample is essentially complete at $24 \mu\text{m}$ for star-forming galaxies, and all residual $24 \mu\text{m}$ non-detection are associated with radio-loud AGN activity (see below).

Using the biweight estimator, we find that for the radio population with $S_{1.4\text{GHz}} > 300 \mu\text{Jy}$ and mid-IR detections ($S_{24\mu\text{m}} > 200 \mu\text{Jy}$), the observed q_{24} values has significantly lower mean and larger scatter for the (non- k -corrected) correlation $q_{24} = 0.30 \pm 0.56$ (it changes to $q_{24} = 0.70 \pm 0.63$ for the sub-sample of sources at $0 < z < 1$).

A histogram of q_{24} for the sources with $S_{1.4\text{GHz}} > 300 \mu\text{Jy}$ is shown in Figure 5. It shows that the bulk of the undetected sources is found below $q_{24} = -0.18$ due to the $200\text{-}\mu\text{Jy}$ threshold adopted for the mid-IR image. This value of q_{24} implies sources three times brighter in radio luminosity than those from our observed mean value $\langle q_{24} \rangle = 0.30$, and ~ 10.5 times brighter than the observed mean value found by Appleton et al. (2004), $\langle q_{24} \rangle = 0.84$. Yun et al. (2001) have defined radio-excess sources as those whose radio luminosity is ≥ 5 times the value predicted from the FIR/radio correlation. In this sense, radio-loud AGN based on $24\text{-}\mu\text{m}$ detections are sensitive to the assumed mean value for the FIR/radio correlation (Appleton et al. 2004, Donley et al. 2005, Boyle et al. 2007). We find that 62 per cent of the radio sources (24 detections and 82 upper limits) plotted in Figure 5 have $q_{24} < -0.18$. These values clearly suggest a large number of radio-loud AGN in this radio flux regime.

It is worth noting that the incompleteness produced by

	Radio sample	q_{24} correlation mean & scatter	Linear regression	M82-like k -corrected q_{24} mean & scatter	Linear regression for the M82-like k -corrected q_{24} 's
(1)	$S_{24\mu\text{m}} > 200\mu\text{Jy}$	0.66 ± 0.39	$q_{24} = (0.85 \pm 0.01) - (0.20 \pm 0.01)z$	0.99 ± 0.32	$q_{24} = (0.94 \pm 0.01) - (0.01 \pm 0.01)z$
(2)	$S_{24\mu\text{m}} > 200\mu\text{Jy}$ & $0 < z < 1$	0.80 ± 0.28		1.03 ± 0.31	
(3)	$S_{1.4\text{GHz}} > 300\mu\text{Jy}$ & $S_{24\mu\text{m}} > 200\mu\text{Jy}$	0.30 ± 0.56	$q_{24} = (0.66 \pm 0.04) - (0.28 \pm 0.03)z$	0.71 ± 0.47	$q_{24} = (0.71 \pm 0.04) - (0.03 \pm 0.03)z$
(4)	$S_{1.4\text{GHz}} > 300\mu\text{Jy}$ & $S_{24\mu\text{m}} > 200\mu\text{Jy}$ & $0 < z < 1$	0.70 ± 0.63		0.95 ± 0.56	

Table 1. Summary of the results presented in Section 3. The linear regressions are based on the detected sources at 1.4GHz and $24\mu\text{m}$, using intrinsic error bars from the source extraction processes.

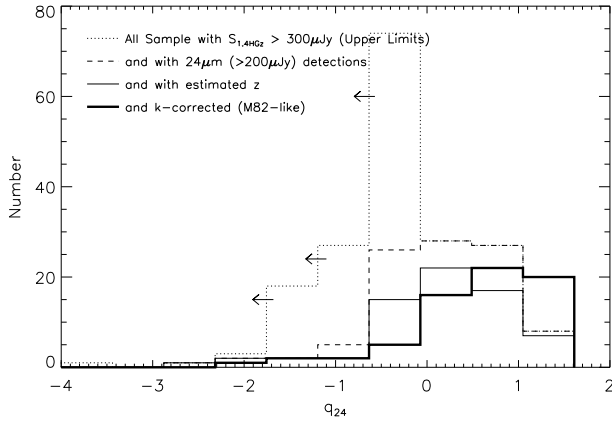


Figure 5. Histogram of the q_{24} values for the radio sources with radio flux densities brighter than $300\mu\text{Jy}$ using different selection criteria. Upper limits are assumed considering $S_{24\mu\text{m}} = 200\mu\text{Jy}$. The distribution for the k -corrected data using a M82-like template is plotted by a thick black line.

sources without photometric redshifts (compare thick continuum and dashed lines in Figure 5) does not introduce significant changes in the mean and scatter of the q_{24} distribution.

The k -corrected mean and scatter values (biweight estimator) for the distribution of sources with $S_{1.4\text{GHz}} > 300\mu\text{Jy}$, mid-IR detections ($> 200\mu\text{Jy}$) and estimated redshifts, changes to $q_{24} = 0.71 \pm 0.47$, 1.25 ± 0.47 , and 0.77 ± 0.48 after using the M82-like, Arp 220-like and Lagache et al. model, respectively. The bottom panel in Figure 2 shows the M82-like k -corrected q_{24} values as a function of redshift for this sub-sample. It suggests a slight descending trend, from $z < 0.5$ to higher redshifts, probably associated with the presence of steeper mid-IR spectra for brighter radio sources, although it is not possible to statistically discriminate a better representative SED between the tested templates.

A simple linear regression to the M82-like k -corrected q_{24} distribution, based on radio sources brighter than $300\mu\text{Jy}$ and detected at $24\mu\text{m}$, is given by $q_{24}(z) = (0.71 \pm 0.04) + (-0.03 \pm 0.03)z$. For this complete radio sample, we also find a flat distribution at 1σ level, suggesting the validity of the FIR/radio correlation up to $z \approx 3.5$. Note, however that even at these bright radio flux densities, at $z \gtrsim 1$ the upper limits may overlap with the mean value found for the correlation, suggesting the possibility of confusion at higher redshifts between radio-loud AGN and those affected by mid-IR features in the SEDs. Future studies with submm and FIR facilities, such as SCUBA-2 and the *Herschel Space Observatory*,

will help to better estimate the total bolometric FIR luminosity, and therefore discriminate between those sources affected by SED features or due to powerful radio AGN activity.

4 RADIO-LOUD AGN ACTIVITY

4.1 The transition from radio-loud AGN to star-forming dominated galaxies

Making use of the M82-like k -corrected data presented in the last section, we have worked out a method of selecting radio-loud AGN from our radio sample, based on different q_{24} thresholds.

It is well known that most powerful radio sources ($> 1\text{ mJy}$) are radio-loud AGN (Condon 1992), but the number counts obtained from deep radio surveys have suggested the appearance of a new, dominant population at fainter radio flux densities. It is well established that this faint radio population may be composed of star-forming galaxies (Condon 1984) and radio-quiet AGN (Jarvis & Rawlings 2004). However, the transition from radio-loud AGN to star-forming galaxies is still not well defined.

To look at the relative fractions of these populations as a function of radio flux density, we use the previous M82-like k -corrected data to identify radio-loud AGN based on different q_{24} cut-off thresholds (Donley et al. 2005). The main assumptions for the following results are the mean and scatter of the $24\mu\text{m}/1.4\text{GHz}$ correlation (§3.3), and the flux thresholds from the radio and mid-IR maps.

Figure 6 shows three different diagrams for the expected fraction of starburst/radio-quiet AGN ('star-forming-dominated' systems²) and radio-loud AGN as a function of the 1.4-GHz flux density. A value of $q_{24} = \langle q_{24} \rangle - 2\sigma_{q_{24}}$ (i.e. 2σ below the mean value) is adopted as the cut-off value of q_{24} used to separate and distinguish 'star-forming dominated' sources from radio-loud AGN. In particular, the cut-off used in the main panel of Figure 6 is at $q_{24} = -0.23$, which in terms of luminosity means that radio-loud AGN are selected by having a radio power ~ 9 times or larger than that predicted by the mean value. All radio sources with measured $24\mu\text{m}$ flux densities and q_{24} values above the threshold are

² The reason we call these objects as star-forming-dominated sources comes only from the fact that they follow the FIR/radio correlation. Although, this is not entirely true because the radio emission from radio-quiet AGN (luminous Seyferts; sources that have been found to follow the correlation) takes the form of jets and suffers the same orientation-dependent beaming effects as the radio-loud AGN, implying it is most definitely AGN-related synchrotron emission.

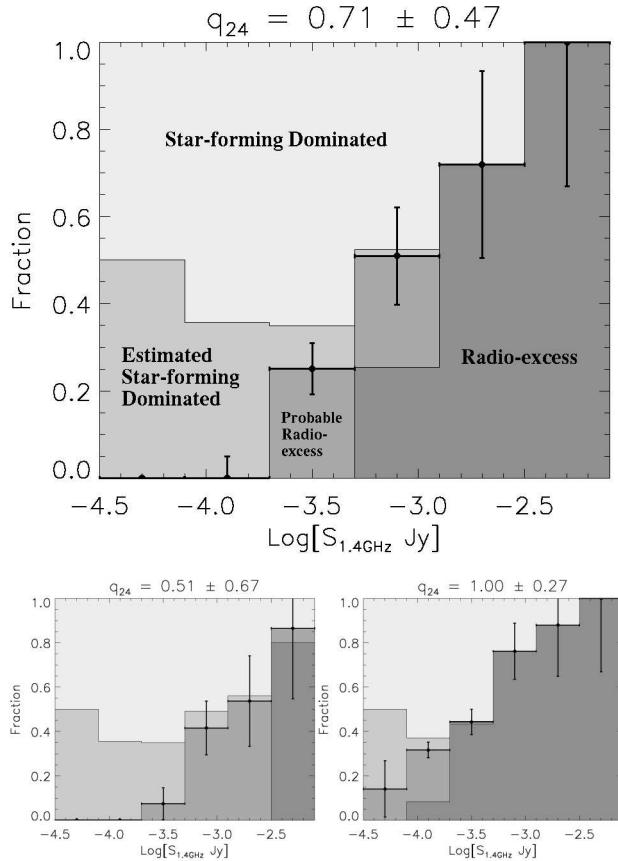


Figure 6. The sub-mJy radio flux transition from radio-excess to starburst-dominated sources based on different q_{24} thresholds using the M82-like k -corrected data. Sources without redshift have been included using a mean M82-like k -correction (+0.33), non varying considerable the results but improving error bars. The “Radio-excess” fraction is composed of those sources detected at $24\mu\text{m}$, or with upper limits, with q_{24} less than 2σ from the mean value of the correlation. The “Star-forming Dominated” fraction is, therefore, that with q_{24} values above the 2σ threshold for radio-excess selection. The “Probable Star-forming Dominated” fraction is based on an estimation which corrects the incompleteness at $24\mu\text{m}$ of the “Star-forming Dominated” sources (see text for details). Hence, all the rest of the sources are very unlikely to follow the $24\mu\text{m}/1.4\text{GHz}$ correlation and are called the “Probable Radio-excess” fraction. Error bars, based on the number counts, are $1-\sigma$ confidence limits given by Gehrels (1986). The main upper panel shows our best estimate of the different populations, based on the results from §3.3. The small panels at the bottom consider the same grey-colour criteria. On the left-hand side we modify the q_{24} mean and scatter based on the higher end of the correlation ($\langle q_{24} \rangle + \sigma_{q_{24}} \approx 1.2$), and on the right-hand side we use the previous Appleton et al. (2004) results.

indicated in Figure 6 as ‘Star-forming Dominated’. The so-called ‘Radio-excess’ fraction corresponds to all those sources detected at $24\mu\text{m}$ with q_{24} below the cut-off value, or undetected but with upper limits below the threshold. The remaining population of sources will be those that are undetected at $24\mu\text{m}$ but have upper limits in q_{24} that lie above the q_{24} threshold for AGN selection. Those will be a mixture of starburst/radio-quiet systems and radio-loud AGN.

We have already said in Section 3 that the faint radio population ($\lesssim 300\mu\text{Jy}$) is affected by incompleteness at $24\mu\text{m}$. In fact, for sources that follow the FIR/radio correlation then, using the threshold for detection in the SWIRE data, we can predict the expected fraction of detections at $24\mu\text{m}$ as a function of radio flux density.

We can then use this to correct the observed fraction of star-forming sources for incompleteness. In order to do so, we ran Monte-Carlo simulations for each radio flux density bin (from Figure 6), using the mean and scatter of the $24\mu\text{m}/1.4\text{GHz}$ correlation, to obtain the probability of detection based on the $24\mu\text{m}$ image threshold at $200\mu\text{Jy}$. The correction for incompleteness to the “Star-forming Dominated” population is called, in Figure 6, the “Estimated Star-forming Dominated” fraction, which is mainly introduced at faint radio fluxes. The reminder of the uncertain population is classified as the “Probable Radio-excess” fraction.

The main panel of Figure 6 shows our best prediction for the transition from radio-loud-AGN-dominated to a star-forming-dominated population at sub-mJy radio fluxes. It makes use of the mean and scatter of the M82-like k -corrected q_{24} values (from §3.3) to define the threshold value and the inputs to the Monte Carlo simulations. It is found that for star-forming sources with $S_{1.4\text{GHz}} = 200 - 500\mu\text{Jy}$ ($10^{-3.7} - 10^{-3.3}$ Jy), or with higher radio fluxes, the expected fraction of counterparts at $24\mu\text{m}$ starts to become complete. Actually, the Monte-Carlo estimation predicts that ≥ 85 per cent of the sources should have counterparts at $24\mu\text{m}$ in this bin (it changes to ≥ 98 per cent considering the Appleton et al. 2004 q_{24} values). This confirms the previous estimation for the complete star-forming radio sample based on a cut-off at $S_{1.4\text{GHz}} = 300\mu\text{Jy}$.

In order to show how the results change with uncertainties in the FIR/radio correlation, the two small panels at the bottom in Figure 6 use an exaggerated scattering for the correlation, and the Appleton et al. (2004) results (left and right hand side, respectively), as indicated by the values above the panels. Each case, however, keeps almost the same fit to the high end of the q_{24} distribution ($\langle q_{24} \rangle + \sigma_{q_{24}} \approx 1.2$).

From our best fit we predict a significant (25 ± 5 per cent) fraction of radio-loud AGN at flux levels of $S_{1.4\text{GHz}} \sim 300\mu\text{Jy}$. The number of radio-loud AGN clearly increases as a function of the radio flux density and above $S_{1.4\text{GHz}} \gtrsim 3.2\text{mJy}$ ($10^{-2.5}$ Jy) essentially all radio sources are radio-loud AGN. At $\sim 50\mu\text{Jy}$ flux density levels, the fraction of radio-loud AGN significantly decreases to zero ($\lesssim 20\%$ from the lower panel estimations), leaving the star-forming dominated systems as the only population at this faint radio flux regime.

These simple analyses suggest that a large number of radio-loud AGN could be selected using deep mid-IR and radio surveys based on a simple radio-excess selection criteria. In terms of the AGN population, we note that our predictions for the “Radio-excess” fraction is just part of the total number of AGN, because many radio-quiet AGN may be included in the ‘star-forming-dominated’ population.

4.2 Host galaxy properties

To explore the optical galaxy host properties of the different populations presented in §4.1, we estimated the rest-frame ($U-B$) colour (limited to sources with estimated redshift) for each source. The colour histograms for the three populations, “Star-forming Dominated” sources, the “Radio-excess” sources, and “All others” (“Estimated Radio-excess” and “Estimated Star-forming Dominated” fractions combined), are plotted in Figure 7.

Considering only the population with radio flux densities $S_{1.4\text{GHz}} > 300\mu\text{Jy}$ (left-hand panel), we find that both the “Radio-Excess” and “All others” populations present clearly redder distributions compared to the “Star-forming Dominated” population. A Kolmogorov-Smirnov (KS) rejects the hypotheses that ei-

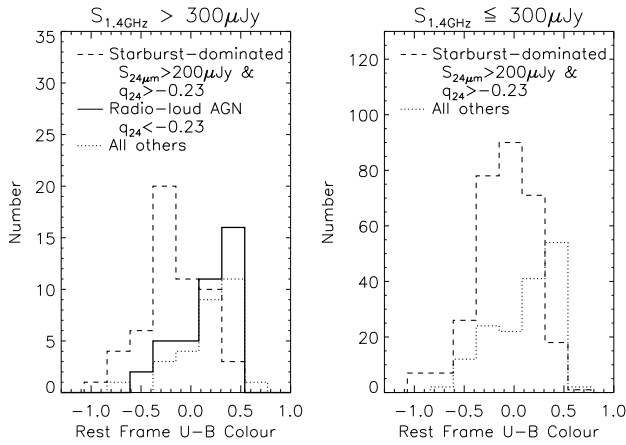


Figure 7. Histogram of rest-frame $U-B$ colours of all sources with estimated redshift in two bins of radio density flux. Dashed, continuum, and dotted lines show the distribution of the “Star-forming Dominated”, “Radio-excess” and “All others” (“Estimated Star-forming” and “Estimated Radio-excess”) fractions, respectively. These correspond to the same ones plotted in the main panel of Figure 6. It shows that the Radio-Excess population has a fundamentally different nature to the Star-forming Dominated sources, and also confirms that at bright radio flux densities ($> 300\mu\text{Jy}$) the “All Others” population is comprised almost entirely of radio-excess objects.

ther the “Radio-Excess” or “All others” sources are drawn from the same parent population as the “Star-forming Dominated” sources at $> 99.999\%$ significance in both cases, proving that they have a different nature. On the other hand, the colour distributions of the “Radio-Excess” and “All others” populations are statistically indistinguishable. This similarity is expected because, as argued in §3.3, at these radio flux densities the “All others” population ought to be composed essentially entirely of “Radio-Excess” sources (see Figure 6). At lower radio flux densities, the “All others” population should contain a mixture of starburst-dominated galaxies and radio-loud AGN, and the right-hand panel of Figure 7 shows that indeed at these lower radio flux densities this population has a more pronounced tail towards bluer $U-B$ colours.

The red colours found for the radio-excess sources may come from the absence of star formation or due to dust obscuration in these sources. Since they do not have detections at $24\mu\text{m}$ – probable absence of re-emission – we suggest that this radio-loud AGN population is hosted in red-galaxies with little or no star-formation. This is potentially a very useful way to detect obscured AGN missed in deep X-Ray surveys, which are responsible of the bulk of the Cosmic X-Ray Background (Ueda et al. 2003).

5 DISCUSSION

Previous studies of the universality of the FIR/radio correlation at high redshift have combined 1.4-GHz data with *ISO* $15\mu\text{m}$ data (Garret 2002) and *Spitzer* 24- and $70\mu\text{m}$ data (Appleton et al. 2004), both showing evidence of a correlation up to $z \sim 1$. More recently, Kovács et al. (2006) and Beelen et al. (2006) have shown evidence for the correlation at higher redshifts, for a sample of 15 submm galaxies ($z \sim 0.5 - 3.5$) and for a handful of distant quasars ($z \sim 2 - 6$), respectively. In this work, despite the difficulty of measuring a reliable bolometric FIR emission, the monochromatic $24\mu\text{m}$ flux densities show a tight correlation with the 1.4-GHz flux density up to $z \approx 3.5$. k -corrections based on an M82-like template

indicate that both the mean and the scatter of the q_{24} values remain constant as a function of redshift (see Figure 3).

The mean and scatter of the distribution of q_{24} values obtained after a M82-like k -correction for all radio sources detected at $24\mu\text{m}$ is $q_{24} = 0.99 \pm 0.32$. This is in broad agreement with the results of Appleton et al. (2004), $q_{24} = 0.84 \pm 0.28$, based on a sample $z \lesssim 1$. However, if our sample is restricted to brighter radio sources for which all star-forming sources would be expected to have been detected at $24\mu\text{m}$, then the mean relation becomes $q_{24} = 0.71 \pm 0.47$, with a scatter about twice that of Appleton et al. The median error value for the q_{24} ’s has been found to be about 0.1 dex, which suggests that this scatter is intrinsic for the correlation and does not come from observational errors. We can conceive of two possible explanations for this increased scatter at higher radio flux densities. First, it may be that, because of the smaller number of sources, some radio-excess objects may fail to be excluded by the biweight estimator, and therefore both bias and increase the scatter of the relation. Second, it may be that for these more powerful sources, the M82-like template (a relatively low luminosity source) is not an accurate representation of the FIR emission of all sources, but that a broader range of SED types is present, increasing the scatter. Figure 2 provides some evidence for this: although a very flat q_{24} distribution is found in the full radio sample (top panel), some redshift variation may be present in the brighter radio sources (lower panel), in particular the presence of a handful of sources with higher q_{24} values at low redshifts $z < 0.5$, which would be more consistent with a steeper mid-IR slope, such as that given by the Arp220-like template.

Recently, Boyle et al. (2007) have found a significantly higher mean value, $q_{24} = 1.39 \pm 0.02$ (2σ away from our estimation) whilst applying stacking techniques (Wals et al. 2005) to ATCA 1.4-GHz images using positions from *Spitzer* detections in the CDFS and ELAIS fields. Their work lacks redshift information, however, and therefore does not include k -corrections. We have shown the relevance of different mid-IR features for high redshift sources at the flux regimes of this work, suggesting a clear underestimation for the intrinsic $24\mu\text{m}/1.4\text{GHz}$ scatter in their work. Also, a stacking analysis for a mixture of star-forming galaxies and radio-loud AGN does not discriminate an exclusive correlation for star-forming galaxies. Since the flux thresholds from our work are similar to their ones, we suggest that selection effects based on different sample selection criteria (from radio or mid-IR detections) may also be affecting the scatter on the $24\mu\text{m}/1.4\text{GHz}$ correlation.

The FIR/radio correlation is not precisely linear, specially in optically selected samples containing faint galaxies. It is expected that the radio emission, in low luminosity galaxies, is more deficient since cosmic rays are more likely to escape from the galaxy (Chi & Worfendale 1990). At redshifts larger than unity the Cosmic Microwave Background might quench the radio emission (Condon 1992) and a cosmic evolution for the magnetic fields cannot be rejected too. Nevertheless, in this work the exploration of more detailed models, showing for example luminosity (or mass) dependencies for the q_{24} parameter, was limited by the uncertainties in photometric redshifts.

A simple radio flux estimation ($S_{1.4\text{GHz}}^{\text{limit}} \approx 35\mu\text{Jy}$) shows that a starburst galaxy with a typical M82 luminosity can be observed up to moderate redshifts only, $z \sim 0.4$. In fact, it is expected that the observed high-redshift high-luminosity Universe is composed mainly of ULIRGs and AGN. ULIRGs are usually related to interacting systems (Sanders et al. 1988) and are expected to suffer strong absorption, implying large k -corrections for the $24\mu\text{m}$ emission. Insights for steeper mid-IR SED at $S_{1.4\text{GHz}} > 300\mu\text{Jy}$

are hinted (bottom Figure 2), however, the lack of a clear scatter excess in the FIR/radio distribution at $z \approx 1 - 2$ (Figure 1) suggests that the bulk of the ULIRG-like high-redshift sources from our sample do not suffer large variations due to silicate absorption. The correlation found in this work is therefore quite unexpected, but suggests that a M82-like mid-IR template, intrinsically coming from a lower luminosity source, is still a good representation for the mid-IR SED of high-redshift star-forming-dominated systems. The M82-like template is also supported by Lagache's ULIRG ($L_{\text{IR}} = 10^{12} M_{\odot}$) model, and particularly leaves Arp 220 as single extreme case. These results are more relevant considering that Kasliwal et al. (2005) estimate that about half of ULIRGs at $z \approx 1 - 1.8$ may be unobserved at $24 \mu\text{m}$ due to silicate absorption at $9.7 \mu\text{m}$ in the Bootes field, a suggestion not particularly supported by our data. For ULIRGs selected in sub-mm observations, their mid-IR SED is still under debate, but templates such as M82 and Arp 220 (Menendez-Delmestre et al. 2007 and Pope et al. 2006, respectively), have been found as good fits for their mid-IR range.

In Section 4, we have shown the capabilities of deep mid-IR and radio imaging for the selection of radio-loud AGN ("radio-excess") based on different cut-offs in q_{24} . We have shown that at $S_{1.4\text{GHz}} > 300 \mu\text{Jy}$, selected radio-excess sources strongly suggests nuclear activity. The radio-excess sources present a redder distribution of rest-frame $U-B$ colours compared with those identified as star-forming-dominated galaxies. This strongly suggest a different nature between the populations selected by the simple q_{24} threshold at -0.23 . Previous population synthesis models (Jarvis & Rawlings 2004) have predicted that radio-excess sources at these flux densities are mainly FRI (Fanaroff & Riley 1974). It is known that FRI do not fall into the standard unified scheme for AGN (Antonucci 1993) and show no bright AGN nucleus. Therefore their red colours indicate that these radio-loud sources do not present significant star-formation activity and/or are hosted in red massive galaxies.

Jarvis & Rawlings (2004) predict that approximately half of the sources with radio fluxes between $100 \mu\text{Jy} \leq S_{1.4\text{GHz}} < 300 \mu\text{Jy}$ present radio-loud activity. We have predicted from our best fit a fraction of $25 \pm 5\%$ at this flux regime, in disagreement by a factor of two with their estimation. Figure 6 shows that Appleton et al. estimation may explain a 50% fraction, although we demonstrated in §3.3 that incompleteness biases the assumptions of those results. On the other hand, Simpson et al. (2006) tentatively suggested a radio-quiet AGN fraction of 20% at this radio fluxes regime, but since radio-quiet sources have been found to also follow the FIR/radio correlation, in this work we are not able to discriminate between this population and starburst galaxies. Therefore, this radio-quiet AGN population remains uncertain.

6 CONCLUSIONS

We have analysed the $24 \mu\text{m}$ properties of a radio-selected sample in order to explore the well-known FIR/radio correlation at high redshifts. We have shown evidence that $24 \mu\text{m}$ data do not give the best estimation of the total bolometric FIR emission, reflected in a considerably larger scatter on the correlation than previous work using longer wavelengths (IRAS/ $60 \mu\text{m}$ – Yun et al. 2001, Spitzer/ $70 \mu\text{m}$ – Appleton et al. 2004). Nevertheless, despite the large scatter, the IR- $24 \mu\text{m}$ /radio-1.4 GHz correlation seems to extend up to redshift ~ 3.5 with roughly the same mean and scatter. The fact that we do not observe considerable variations in the correlation as a function of redshift, mainly seen on the well defined

upper end of the k -corrected q_{24} distribution (see top Figure 2 & 3), highly suggests its validity all the way back to primeval times. This is the first evidence for the extension of the correlation over this very wide range of redshifts.

Statistically, the correlation is described by the basic observable parameter q_{24} , the ratio between the flux densities at $24 \mu\text{m}$ and 1.4 GHz, respectively. The q_{24} factor parameterise the link (in the local Universe at least) that star-forming galaxies have between the synchrotron emission, from cosmic rays accelerated by massive supernovae explosions, i.e. the massive end of the mass function in galaxies, with the reprocessed UV photons re-emitted by the dust at FIR wavelengths. Besides an intrinsic scatter for the correlation, the presence of an AGN may also modify the mid-IR spectra and the radio emission, biasing, and therefore increasing the scatter on a q_{24} -based correlation. We found a mean value (biweight estimator) of $q_{24} = 0.30 \pm 0.56$ for the observed and $q_{24} = 0.71 \pm 0.47$ for the k -corrected (M82-like) data based on an expected complete radio sample ($S_{1.4\text{GHz}} > 300 \mu\text{Jy}$) at $24 \mu\text{m}$.

Three different k -corrections have been tested: two based on well-known local starburst sources (M82 and Arp 220) and one on a SED ULIRG model (Lagache et al. 2004). The main difference introduced by using different templates is caused by the silicate absorption feature at $\sim 10 \mu\text{m}$ being redshifted into the observed $24 \mu\text{m}$ band at $z \approx 1 - 2$ (Figure 1). Based on the smallest scatter found for q_{24} data, we propose an acceptable k -correction given by an M82-like mid-IR template, which suggests no strong evidence for extreme silicate absorption in the bulk of our sample. We do, however, find tentative evidence for a steeper mid-IR spectrum than M82 for brighter radio sources $> 300 \mu\text{Jy}$, in order to explain the slight offset from the correlation for sources with $z < 0.5$.

We have found a clear dependency for the detected number of star-forming-dominated galaxies (starburst and radio-quiet AGN) as a function of the radio flux density. Making use of the derived $24 \mu\text{m}/1.4\text{GHz}$ correlation, and the flux density threshold from the $24 \mu\text{m}$ image, we ran Monte-Carlo simulations to estimate the incompleteness at $24 \mu\text{m}$, and therefore the intrinsic fraction of star-forming-dominated galaxies. This allowed us to estimate the probable fraction of radio-loud AGN and to describe the transition from AGN-dominated to star-forming-dominated galaxies at faint radio flux densities ($\lesssim 1 \text{ mJy}$). Our best-fit estimation predicts a significant fraction ($25 \pm 5\%$) of radio-loud AGN at $S_{1.4\text{GHz}} \sim 300 \mu\text{Jy}$, rising quickly to become a dominant AGN population at brighter radio flux densities ($> 1 \text{ mJy}$), and falling towards zero (certainly $\lesssim 20\%$) at fainter fluxes. These results are in broad agreement with previous studies (e.g. Condon 1984).

We have also shown that the rest-frame $U-B$ colours, of the sources that are expected to be radio-loud AGN, have a redder distribution than the starburst/radio-quiet AGN galaxies (Figure 7), strongly suggesting a different nature between the sources selected by our simple $q_{24} = -0.23$ threshold. These radio-excess sources seem to be hosted in red galaxies with little or no star-formation implied by the non-detection at $24 \mu\text{m}$. This is therefore an extremely promising way to select obscured Type-2 AGN (Comastri et al. 1993), with a radio-loud nature, which are missed by deep X-ray observations. Nevertheless, future spectroscopic follow-up of these sources, and also a better description of the FIR emission, is needed to fully test this method.

ACKNOWLEDGEMENTS

This paper was supported by a Gemini–STFC research studentship. E.I. thanks to A. Pope, G. Lagache, P. Lira & B. Brandl for templates and useful comments to the paper. P.N.B., R.M., I.R.S. and O.A. acknowledge support from the Royal Society.

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